Using FFAGs in the Creation of Muon Beams

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What are FFAGs?

- **F**ixed **F**ield **A**lternating **G**radient Accelerator
- Fixed field:
  - Ramping magnets limit acceleration rate
  - Applications requiring rapid acceleration
- Alternating gradient:
  - Keep horizontal aperture small
  - In contrast to cyclotrons
- Wide energy acceptance in ring

Time of Flight Dependence on Energy

- Time of flight depends on energy
- Acceleration: must synchronize to RF
  - Vary the RF frequency
    - High losses if done too quickly
  - Other techniques, described later
- Cyclotron isochronous
  - High fields at relativistic energies

Proton Drivers

- Requirements for neutrino factory
  - Pulsed, somewhat high repetition rate ($\approx$50 Hz)
  - 7–8 GeV or higher energy
- Energy too high for cyclotrons
- Repetition rate difficult for synchrotron
- Linac expensive, especially at higher energies
- Strong motivation to use FFAGs

Proton Driver
Types of FFAGs

- Scaling FFAG
  - Studied in Japan, but nonrelativistic
  - Constant tune
- Linear non-scaling FFAG
  - Reduced aperture
  - Tunes not constant
    - Limits energy range of single stage, but may win with smaller apertures

Proton Driver
Types of FFAGs

- Nonlinear, non-scaling FFAGs
  - Tunes constant
  - Aperture advantages?
  - Extremely nonlinear
    - High fields
    - Dynamic aperture issues?
  - Proposed in ISS neutrino factory study

Linear Non-Scaling FFAG

- Achieves large dynamic apertures
- Requirements
  - Simple cells, all identical
    - Linear resonances driven only by errors
  - Highly linear magnets
    - Nonlinear resonances driven only weakly
  - Rapid acceleration
    - Pass through weak resonances quickly

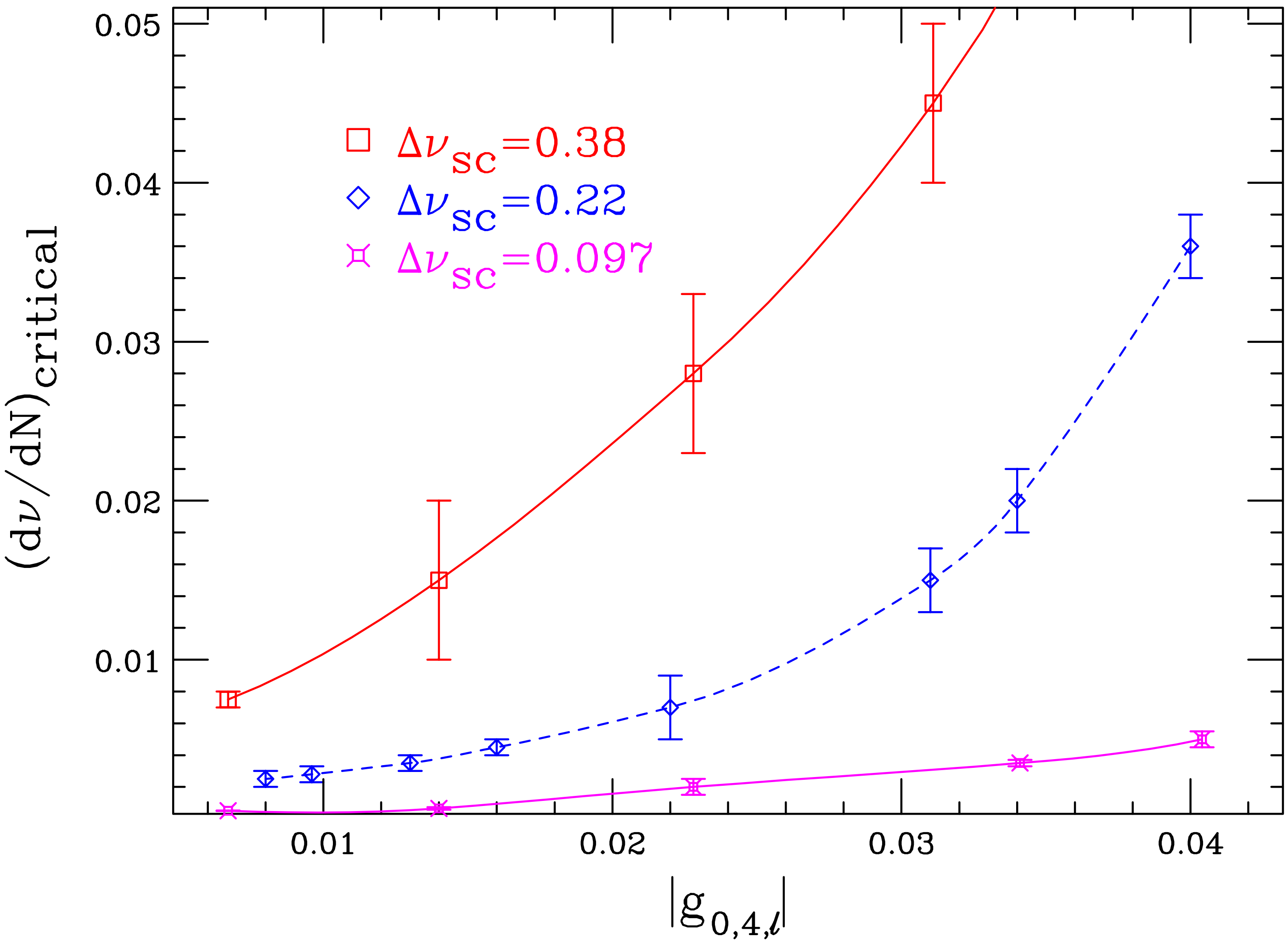
Space Charge

- Significant effect in any proton driver
- Self-fields between particles
- Electric field pushes apart, magnetic field pulls together
  - Cancel at speed of light
  - Goes as $1/\gamma^2$
- Increases with larger current

Space Charge

- Particular issue for linear non-scaling FFAG
  - Passes through all tunes
  - Acceleration rate isn't *that* fast
    - Limited by rate of RF frequency change, gradient
    - Variable frequency requires low frequency
    - No high gradient at low frequency, low Q
  - Space charge drives nonlinear resonances (Lee)

Acceleration Rate Required by Space Charge (S. Y. Lee)



Space Charge

- Constant-tune designs preferred
  - Avoid space-charge nonlinear resonance tunes
- Variable-tune solutions
  - Linear non-scaling FFAG
  - Need to determine required acceleration rate
  - R&D on rapid acceleration
    - Rapid frequency variation
    - High gradient

Space Charge
MINHA Experiment

- Proposed experiment (Ruggiero)
- Study space charge effects in linear non-scaling FFAGs
- Use low-energy electrons
- Help determine required acceleration rate

Harmonic Number Jump

- Avoid varying RF frequency
- Use high-gradient, high-Q RF cavities
- Time of flight different on each turn
  - Same RF phase each pass
  - Different number of RF periods
- Energy gain different for each turn
  - Cavity voltage depends on position
  - Wide cavity for high frequency

Beams with Large Energy Spread

- Use energy acceptance of FFAG
- No net acceleration
  - But generally have some RF
- Transmit large energy spread beams
- Examples being built in Japan
  - PRISM
  - ERIT

Ionization Interactions

- Ionization interactions used in making neutrino beams
  - Ionization cooling of muons
  - Ion production for beta beams (Rubbia)
- Energy straggling generates large energy spread
  - 10–20% for muon cooling
  - Small (?) for ion production (0.5% RMS)
- No acceleration: RF fixed frequency

Ionization Interactions FFAG Applicability

- Muon cooling
  - FFAGs have dispersion: 6-D cooling
  - Focusing not as strong as solenoid channels
  - Maybe better energy acceptance
  - Probably only useful in early stages
- Ion production
  - ERIT is very similar to Rubbia’s system
  - Ion beam operates in different regime (?)
    - Low energy spread, FFAG not needed (?)

Muon Acceleration

- Different operating regime from proton driver
  - Acceleration exceedingly rapid: 5–20 turns
  - No time to adjust RF frequency
  - Space charge unimportant
- Motivation for FFAGs is cost reduction
  - RF systems most expensive part of machine
  - Make more passes through RF (than RLA)
    - Also reduces average power consumption

Challenges of Accelerating Muons

- Avoid decays: rapid acceleration ($>$1 MV/m average)
  - No time to ramp magnets
  - No time to adjust RF phase
- Large transverse emittance
- Large longitudinal emittance
- Beam loading can't be ignored
  - Especially true with multiple cavity passes

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Muon Acceleration with FFAGs Accelerating Mode

- No time to add energy to cavities between turns
  - Too much power required
  - Initial stored energy used for all passes
  - RF phase constant
- Time of flight depends on energy
- Beam arrives at different RF phases
- Will eventually leave crest
- Beam loading eventually limits passes also

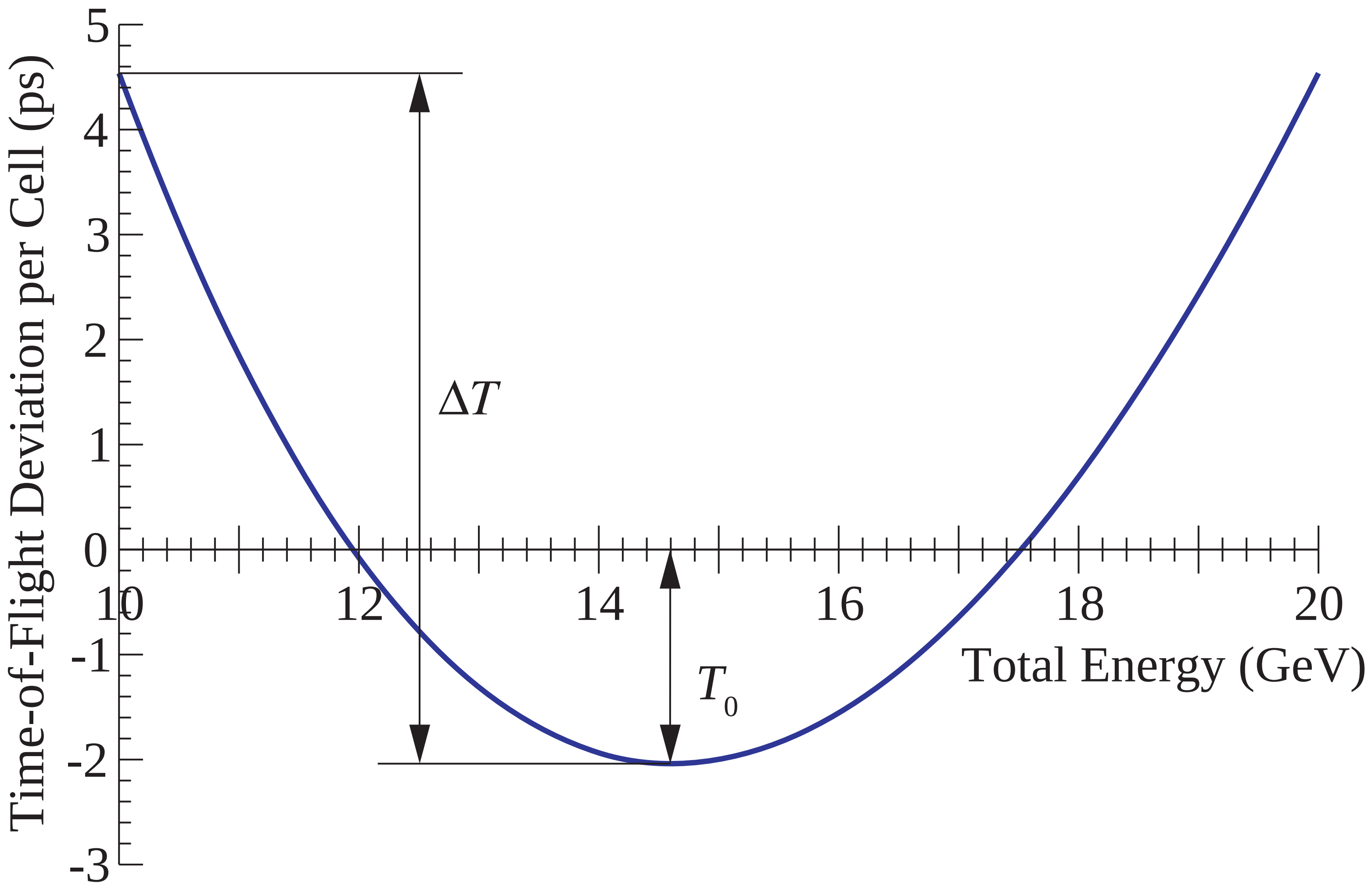
Muon Acceleration
Linear Non-Scaling FFAGs

- Muon acceleration: lack some problems found in proton acceleration
  - No nonlinearities from space charge
  - Accelerate very rapidly through resonances
- Thus keeping tune constant not important
  - Except one problem later. . .
- Horizontal aperture smaller than scaling FFAG
  - Most bending occurs in defocusing magnet

Muon Acceleration Linear Non-Scaling FFAGs

- Beams highly relativistic
  - Energy variation of time from path length
- Isochronous within energy range
  - Consequence of small horizontal aperture
  - Small time of flight variation
  - Longer time before drifting off RF crest
  - Allows high RF frequencies (200 MHz)
    - Smaller time variation, shorter RF period
    - Compatible with cooling

Muon Linear Non-Scaling FFAGs
Time of Flight Variation



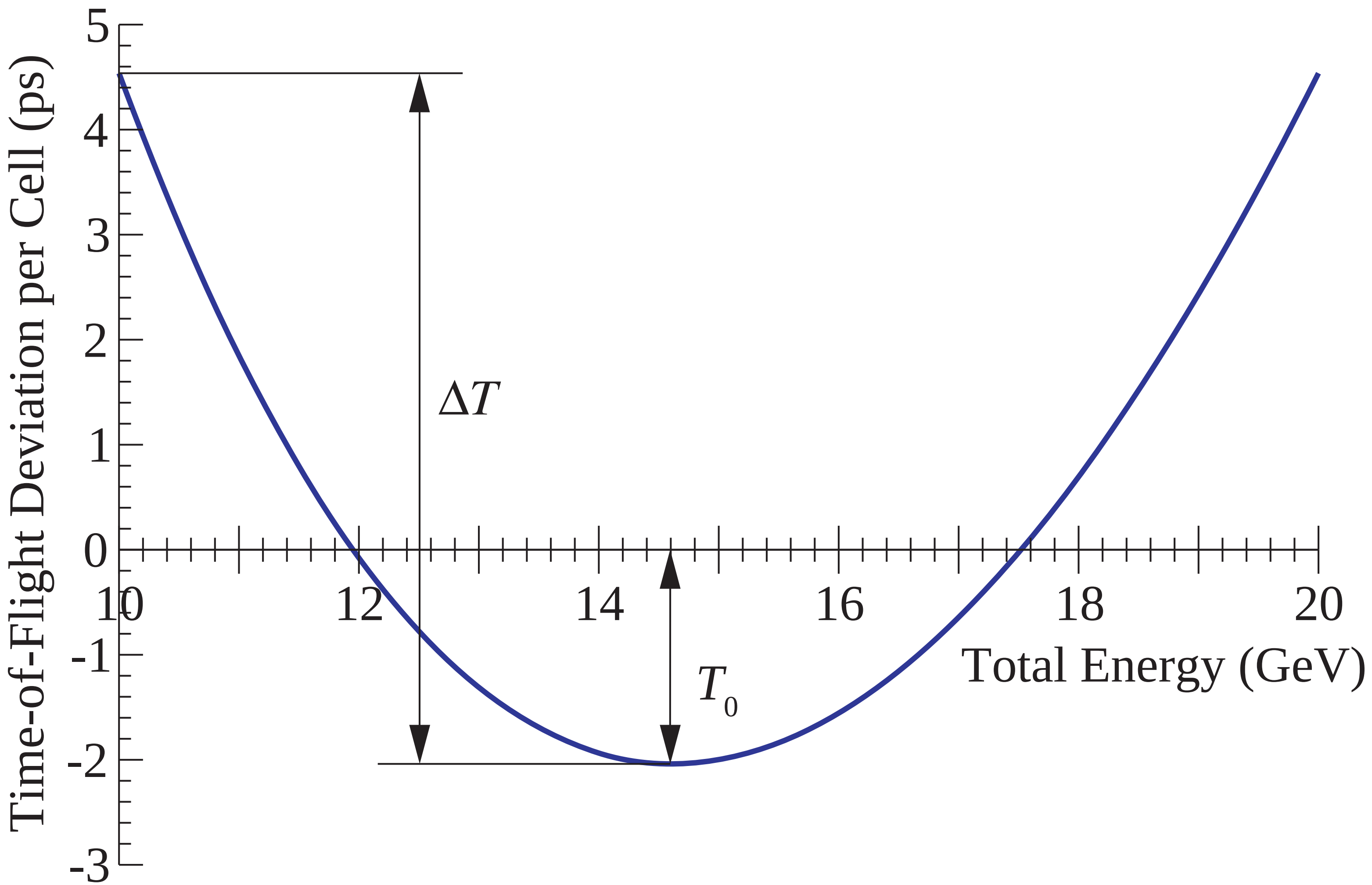
Muon Acceleration
Linear Non-Scaling FFAGs

- Higher energy FFAGs more efficient
- Required circumference increase more slowly than energy
  - Related to magnet apertures
- Fewer turns at lower energy
- Don’t compete with RLAs (4–5 turns) at low energies (below 2.5 GeV)

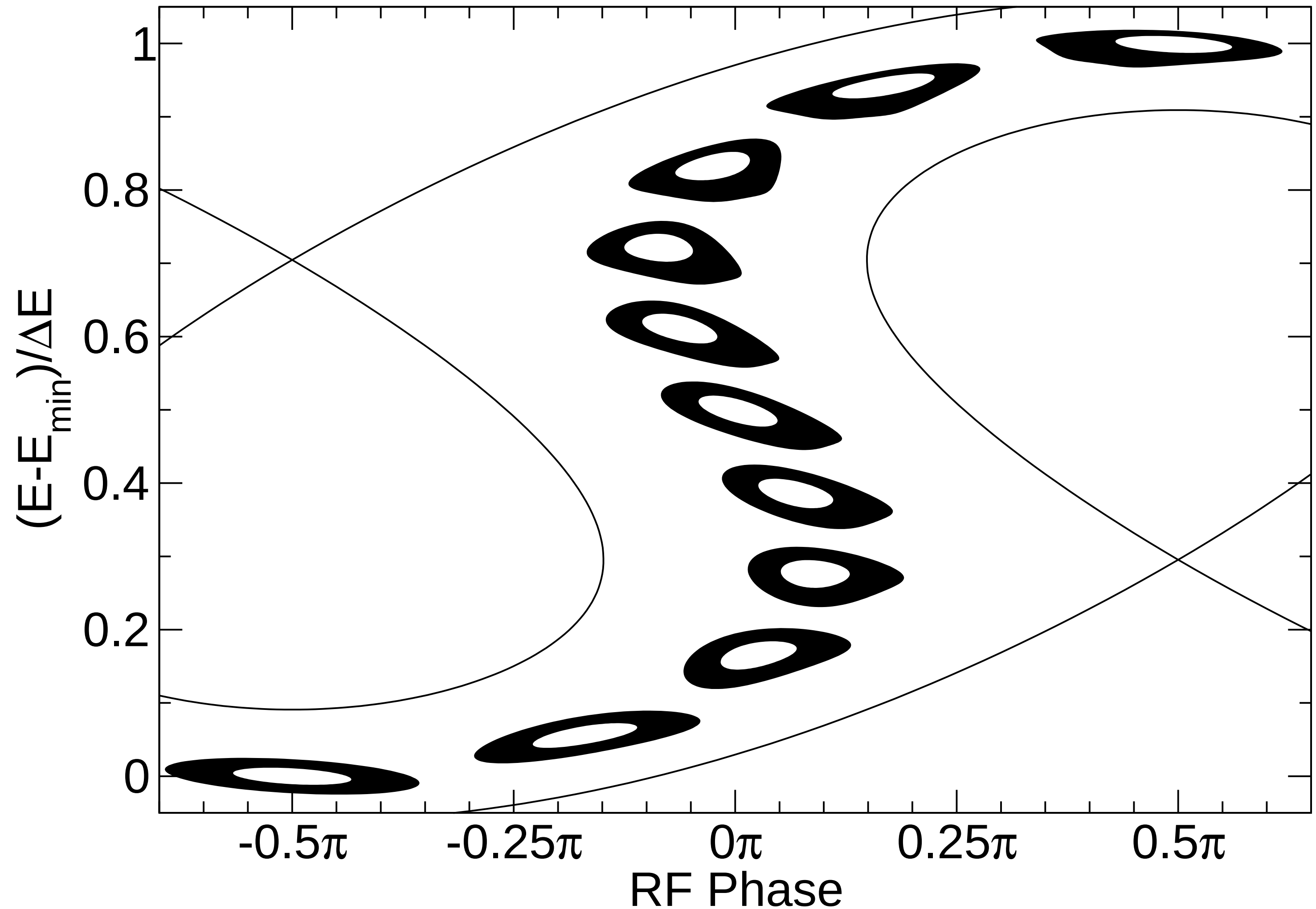
Muon Linear Non-Scaling FFAGs Longitudinal Dynamics

- Time vs. energy parabolic
- Allows 2 energies synchronized to RF
- Cross RF crest 3 times
- Maximizes time before leaving RF crest
    - More turns

Muon Linear Non-Scaling FFAGs Time of Flight Variation

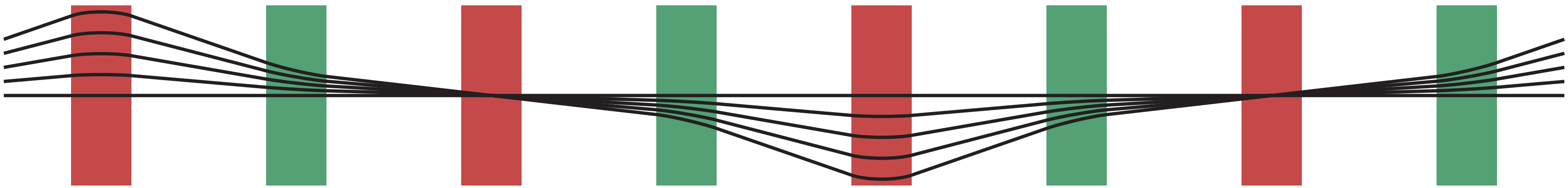


Muon Linear Non-Scaling FFAGs Longitudinal Dynamics



Muon Linear Non-Scaling FFAGs Time vs. Transverse Amplitude

- Beams have large transverse size/angles
- Larger transverse amplitude, longer particle path length
- Proportional to tune variation with energy
- Less problem with synchrotron oscillations
  - Late particles become early



Muon Linear Non-Scaling FFAGs Time vs. Transverse Amplitude

- Fixes for the problem
  - Most promising: increase average RF gradient
    - Cuts effect in half
    - Significant reduction in passes
    - Importance of high gradient cavities
  - More cooling!
  - Reduce tune variation with energy
    - Nonlinear magnets: dynamic aperture

Linear Non-Scaling FFAGs
The EMMA Experiment

- Linear non-scaling FFAGs have never been built
- Test our understanding of dynamics
  - Without complication of space charge
- The EMMA experiment
- More in next talk. . .

Scaling FFAGs

- Reasons to use
  - No time of flight variation with amplitude
  - Greater energy range per stage
    - Increased apertures: not cost effective?
- Reasons not to use
  - Larger apertures than non-scaling
  - Forced to low frequency RF

Scaling FFAGs Magnet Apertures

- Larger apertures than non-scaling FFAG
  - Most bend must (?) be in focusing magnet
- Could use warm or superferric magnets
  - Horizontal aperture not as important to cost
  - Circumference may be OK at these energies
    - Especially low energy stages

Scaling FFAGs
RF Frequency

- Time of flight varies monotonically with energy
- Larger time variation with energy than non-scaling
- Cross crest twice, not 3 times
- Requires low ($\approx$15 MHz) RF frequency to stay near crest
  - High gradients challenging at this frequency
  - Incompatible with efficient 200 MHz capture/cooling system

Scaling FFAGs
Harmonic Number Jump

- Consider harmonic number jump
- Same difficulties as proton driver, plus. . .
- Must fill ring with cavities
  - All cavities can't have phase synchronized
  - Possible for limited number of turns
    - Many different frequencies
  - Only one muon sign
- Difficulty keeping long trains synchronized

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Nonlinear Non-Scaling FFAGs

- Two conditions one could try to meet
  - No time of flight variation with energy
    - Not so important: aperture, circumference, and average gradient determine cost
  - No tune variation with energy
    - Help time variation with transverse amplitude
- Examples thus far have insufficient dynamic aperture for muons

Beam Loading

- Beam extracts energy from cavities
- Different bunches in train gain different energies
  - No synchrotron oscillations to fix
  - Can be corrected later
- Multiple proton bunches per cycle
  - Must follow in rapid succession (40 μs total)
  - No time to restore cavity energy
    - Many passes: more energy extracted

Conclusions

- FFAGs: applications in making neutrino beams
  - Proton drivers
  - Ionization: ion production, muon cooling (?)
  - Muon acceleration
- Proton driver
  - Allow rapid acceleration to high energies
- Muon acceleration
  - Allow large number of passes through RF

Conclusions
R&D Needed

- RF manipulation in proton FFAGs
  - Rapid frequency variation, high gradient
  - Harmonic number jump
- Space charge limits in proton FFAGs
- Optimal handling of large transverse amplitude
- Scaling FFAGs for muons
- Beam loading in muon FFAGs
- FFAG experiments: EMMA, MINHA